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雑誌名	東北大学電通談話会記録
巻	86
号	2
ページ	54-57
発行年	2018-08
URL	http://hdl.handle.net/10097/00123412

修士学位論文要約（平成 29 年 9 月）

擬似· 拡張位相整合自発パラメトリック下方変換素子を用いた高効率光子対発生

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Efficient Photon-Pair Generation via Quasi and Extended Phase Matching Devices Based on Spontaneous Parametric Downconversion

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In quantum information processing, spontaneous parametric downconversion (SPDC) has played an important role in entangled photon generation and heralded single photon generation. In this work, we use SPDC-based devices for polarization entanglement generation and spectrally pure heralded single photon generation with high efficiency and performance. We utilize a two-section periodically-poled lithium niobate (PPLN) waveguide having two poling periods in series for efficient polarization entanglement generation. We observed 1×10^7 pairs/sec/mW generation efficiency of the entangled photon pairs with high fidelity (0.92) to the ideal Bell state. In collaboration with the F. Wong's group of MIT, we investigated frequency-uncorrelated photon pair generation using a controlled-poled KTP (cpKTP) device, which provides a Gaussian-shape phase matching function. The joint spectra exhibited the highest spectral purity (0.99) ever reported. We also investigated a frequency uncorrelated source based on a periodically-poled KTP (PPKTP) waveguide device. We obtained high generation efficiency (4.7×10^6 pairs/sec/mW) and spectral purity (0.88) estimated from the joint spectra. We also carried out intensity correlation measurements for generated photons in order to verify the spectral purity.

1. Introduction

In quantum processing applications, the spontaneous parametric downconversion (SPDC) process has been a key element as heralded single-photon sources and entangled photon sources. An optical quantum system can take advantage of well-developed modern optical communication systems for long distance transmission in implementing quantum info-communication protocols such as quantum cryptography. Also, the features of easy generation and detection of photons make optical quantum applications the subject of much attention, e.g., optical linear quantum computing, quantum communication, and quantum metrology. Most of these applications need high performance photon sources that emit heralded single photons or entangled photons. To date, we have developed a number of sources for polarization entangled photons and heralded single photons using SPDC. Since SPDC has benefits such as a simple setup, high efficiency, and high flexibility, it is the most commonly used scheme for photon pair generation. In this work, we combine SPDC with techniques such as quasi-phase matching (QPM) and group velocity matching (GVM), and introduce unique SPDC-based sources for highly efficient generation of polarization entangled photons and spectrally pure heralded single photons. Our aim in this work is developing such high performance photon sources that are suitable for future optical quantum applications.

2. Efficient polarization entangled photon pair generation via PPLN waveguide

Polarization-entangled photon sources play an import role in optical quantum technologies such as quantum teleportation, quantum computation, and quantum cryptography. The most established method so far used for entangled photon generation is the SPDC process in nonlinear crystals, such as $LiNbO_3$ (LN) and $KTiOPO_4$ (KTP). In recent years the technique of QPM together with waveguide structures has been developed as a fundamental tool for photon pair generation. For instance, PPLN (periodically-poled LN) and PPKTP have been used as efficient sources for preparing entangled photons in the telecom band. We proposed a post-selection free scheme for polarization entangled photon generation by utilizing type-II PPLN having two

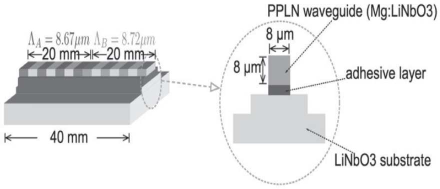

Fig. 1 Schematic view of the waveguide. A ridge waveguide consists of a MgO-doped $LiNbO_3$ core adhered on a $LiNbO_3$ substrate.

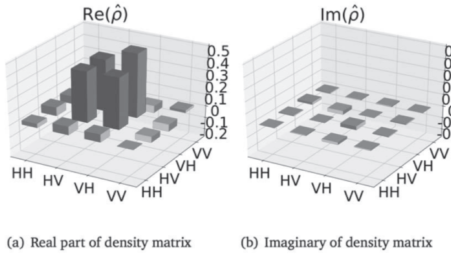

Fig. 2 Real (left) and imaginary (right) parts of the density matrix reconstructed by quantum state tomography.

poling periods with different period length[1]. The technique has recently been demonstrated in bulk PPLN with a series poling periods structure[1], and also with an interlaced poling period structure[2]. We developed a waveguide device consisting of ridge waveguides with two sequential poling periods in each waveguide as a simple and efficient entanglement source. The waveguide device was fabricated by Oki Electric Industry implementing our design shown in Figure 1; this rough sketch gives a schematic view of our waveguide structure. Our waveguide consists of MgO-doped $LiNbO_3$ core (8 μm × 8 μm section size) adhered on a $LiNbO_3$ substrate in order to guide both orthogonal polarization modes. Our waveguide contains two parts with different poling periods (Λ_A = 8.67 μm and Λ_B = 8.72 μm), each of which has the length of L=20 mm. The signal and idler photons have horizontal (H) and vertical (V) polarizations, respectively. Using this device, we expect that the first (second) section emits photons with the wavelength λ_1 in the H (V)-polarization and λ_2 in V (H)-polarization. To do so, we tune the emission wavelengths of signal and idler photons by tuning, for instance, the device temperature. The generated state results in the superposition of the photon pair states emitted from the two sections. Thus, if we label the photons in terms of their wavelength, the generated state is polarization-entangled so that

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{H}\rangle_1|\mathrm{V}\rangle_2 + e^{i\phi}|\mathrm{V}\rangle_1|\mathrm{H}\rangle_2\right) \quad (1)$$

where the labels 1 and 2 refer to photons of λ_1 and λ_2, respectively, ϕ is the relative phase originating from the difference in birefringent group delay between the two photon pair states.

In our experiment, the waveguide device was pumped by a CW laser (wavelength: 772 nm). An InGaAs spectrometer was used for observing the SPDC spectra. We see that the signal photon emitted from one section and the idler from the other section have the identical wavelengths at 16°C. At this temperature, the emission spectra for signal (H) and idler (V) photons are almost identical, having two peaks located at λ_1 =1533 nm and λ_2 =1556 nm. Thus, the condition to obtain the polarization entangled state (Eq. 1) is fulfilled. In the experiment of generation efficiency measurement, we have observed a very high generation efficiency n_{eff} = 1× 10^7 pairs/sec/mW. Comparing it to the previous work with PPLN bulk crystal[1], we obtained 100 times higher efficiency due to our waveguide structure. In polarization correlation measurement experiments we observed high visibility (0.92) for both horizontal-vertical and ±45° bases, which implies quantum correlation between the generated photons. To fully characterize the quantum state of polarization correlation, we carried out a quantum state tomography measurement, by which we reconstructed the density matrix of the measured state, as shown in Fig. 2. We estimated the fidelity (F) from our reconstructed density matrix to verify how close the obtained quantum state is to an ideal Bell state. The obtained fidelity F = 0.92 shows that the generated state with our waveguide device is very close to an ideal Bell state.

3. Generation of frequency uncorrelated photon pairs with high spectral purity via cpKTP device

Optical quantum applications highly rely on the performance of non-classical interference between individual photons. High visibility of interference between photons requires photons be completely indistinguishable in all the degrees of freedom. However, indistinguishability of heralded single photons generated by normal SPDC is limited by imperfect spectral purity of the single photon; the spectral purity is degraded by the frequency correlation between signal and idler photons. In this regard, PPKTP with GVM condition can

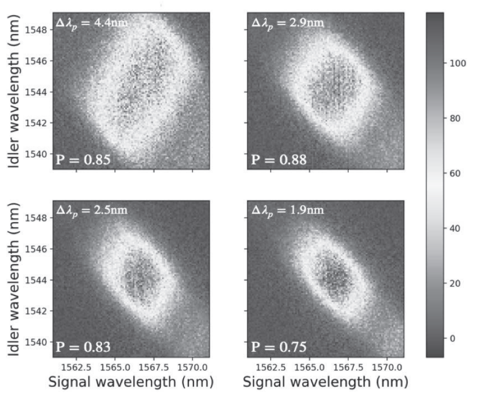

Fig. 4 Joint spectra of signal and idler photons generated from a PPKTP waveguide for various pump bandwidth.

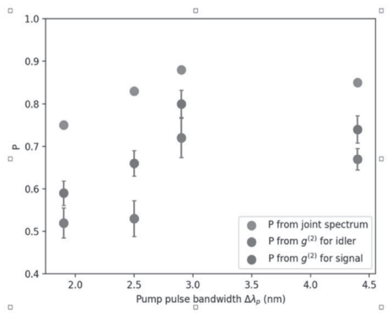

Fig. 5 Spectral purity obtained from Schmidt decomposition of the joint spectra (grey dots), from the intensity correlation measurement for signal beam (blue dots), and from the intensity correlation for idler beam (red dots).

generate frequency uncorrelated photons to achieve high visibility quantum interference[3]. However, normal SPDC process including GVM has a cardinal sine (sinc) shaped phase matching function with which it is difficult to wash out the frequency correlation completely. As a visiting student, I worked in Franco Wong's group at MIT with their unique cpKTP device, which has a modified poling duty cycle providing a Gaussian shape phase matching function. Using this device, we observed the joint spectra of the SPDC and verified that the spectral purity is as high as 0.99, that is the highest purity ever reported. The details of this research are published in Ref. 4

4. Generation of frequency uncorrelated photon pairs with efficiency via PPKTP device

With the growing interest in highly efficient and spectrally pure heralded single photon generation, waveguide-based PPKTP devices attract much attention. However, unlike bulk PPKTP[3] and cpKTP[4], the joint spectra of waveguide devices have an elliptical shape due to the change of GVM caused by the shift of refractive index[5]. In this work, we characterized the GVM and the SPDC spectra of a PPKTP waveguide and evaluated the spectral purity.

Our PPKTP waveguide device is a 10 mm long chip with channel waveguides formed by Rb ion exchange. The device is designed for type-II SPDC at telecom wavelength with a poling period of 136.986 μm. We calculated the refractive index dispersion of the PPKTP waveguide using the finite element method (FEM). We found that the GVM condition of the waveguide structure shifts to a longer wavelength compared to the bulk PPKTP and is not perfect at the telecom wavelength. We experimentally confirmed the dispersion by measuring the SPDC spectra while changing the pump wavelength. Nevertheless, this device can still be used as a spectrally pure heralded single photon source, even though the purity would not be perfect. In the following experiment, we used the pump wavelength centered at 778 nm and the center wavelengths of signal and idler photons were 1544 nm and 1567 nm, respectively. It is noteworthy that we obtained a generation efficiency of 4.7×10^6 pairs/sec/mW, which is almost 100 times higher than that obtained using bulk PPKTP[3].

In order to evaluate the spectral purity of generated photons, we carried out joint spectrum measurement varying the pump bandwidth as shown in Fig 4. By their Schmidt decomposition, we found that the highest purity was P= 0.88 at the pump bandwidth of $\Delta\lambda_p$=2.9 nm. The obtained purity was slightly lower than the previously reported value (0.91)[5]. From our simulation assuming the sinc shaped phase matching function, we expect the purity to be as high as 0.96. Unwanted spectral components introduced by non-uniform effective refractive index of our device might degrade the spectral purity.

So far, Schmidt decomposition of joint spectra is a commonly used method to evaluate the spectral purity. However, in principle, this method gives the upper bound of purity, because of two reasons. The first one is that Schmidt decomposition in this method is performed on intensity join spectra, although in principle Schmidt decomposition should be performed in terms of complex amplitude including phase information. The second reason is that joint spectra can only be measured in a finite wavelength range; it is equivalent to apply a bandpass filter causing higher purity values.

To verify the purity, we carried out another method, i.e., intensity correlation measurements for signal and idler photons. It is known that SPDC emits photons into each single spectrotemporal mode obeying a thermal photon number distribution. However, if the spectral mode is not pure containing multiple modes, the photon number distribution is averaged over the multiple modes and thus changes from geometric to random (Poisson) distribution with increasing mode number. In terms of intensity correlation ($g^{(2)}$) measurement, this means that $g^{(2)}(0)$ changes from $g^{(2)}(0)=2$ from the single (pure) mode case to $g^{(2)}(0)=1+1/N$ in the multiple mode case, where N is the effective mode number into which photons are emitted. In this method, the purity is estimated as $P=1/N=g^{(2)}(0)-1$. In the experiment, we measured $g^{(2)}(0)$ of signal and idler photons for the pump bandwidths used in the joint spectrum measurement. In Fig. 5, the purity values thus obtained are shown in comparison with those obtained from the joint spectra. The purity exhibited the highest values at a pump bandwidth $\Delta\lambda_p$=2.9 nm; three kinds of measurements show the same dependencies on the pump bandwidth. Thus we confirmed at least qualitative correspondence between these three measurements. The highest purity obtained using the intensity correlation of signal (idler) photons was 0.80±0.03 (0.72±0.05), which was smaller than that (0.88) obtained from the joint spectra. This is reasonable if one takes into account that the purity obtained from the joint spectra gives its upper bound, as mentioned above. The lower purity value obtained from the intensity correlation of idler photons might originate from unwanted spectral components leaked to the idler photon detection. Thus, the purity value 0.80±0.03 obtained from the intensity correlation of signal photons would be the most reasonable estimation of the spectral purity of photons emitted from our device, although comparison with other reported results is made in terms of commonly used methods, i.e., joint spectra.

5. Conclusion

Firstly, we developed a type-II SPDC PPLN waveguide device containing two sections with different poling periods in series. This device was designed for efficient polarization entanglement generation at telecom wavelength. In comparison with previous works we observed much higher generation efficiency $n_{eff} = 1\times 10^7$ pairs/sec/mW. In terms of quantum state tomography measurement we showed that the generated state is very close to an ideal Bell state with fidelity F = 0.92.

Secondly, in collaboration with Franco Wong's group at MIT, we worked with the cpKTP device. From the joint spectrum measurement, we obtained the purity of P=0.99, which is the highest purity ever reported for SPDC photons.

In the third project, we developed a spectrally pure single photon source based on PPKTP waveguide structure. The generation efficiency of this device was 4.7×10^6 pairs/sec/mW, which was 100 times higher than that of the bulk crystal. We used two methods to verify the spectral purity: (1) Schmidt decomposition of a joint spectra and (2) intensity correlation measurements. We found even though there is no perfect GVM in the waveguide device, we can still obtain high purity (P~0.80) single photons.

We consider these devices and techniques are useful for future quantum applications that require efficient generation of entangled photons and indistinguishable single photons.

References

1) W. Ueno, F. Kaneda, H. Suzuki, S. Nagano, A. Syouji, R. Shimizu, K. Suizu, and K. Edamatsu, Opt. Exp. **20**, 5508--5517 (2012).
2) H. Herrmann, X. Yang, A. Thomas, A. Poppe, W. Sohler, and C. Silberhorn, Opt. Exp. **21**, 27981 (2013)
3) M. Yabuno, R. Shimizu, Y. Mitsumori, H. Kosaka, and K. Edamatsu, Phys. Rev. A **88**, 010302 (2012).
4) C. Chen, C. Bo, M.Y. Niu, F. Xu, Z. Zhang, J.H. Shapiro, and F.N.C. Wong, Opt. Exp. **25**, 7300-7312 (2017).
5) G. Harder, V. Ansari, B. Brecht, T. Dirmeier, C. Marquardt, and C. Silberhorn, Opti. Exp. **21**, 13975 (2013)